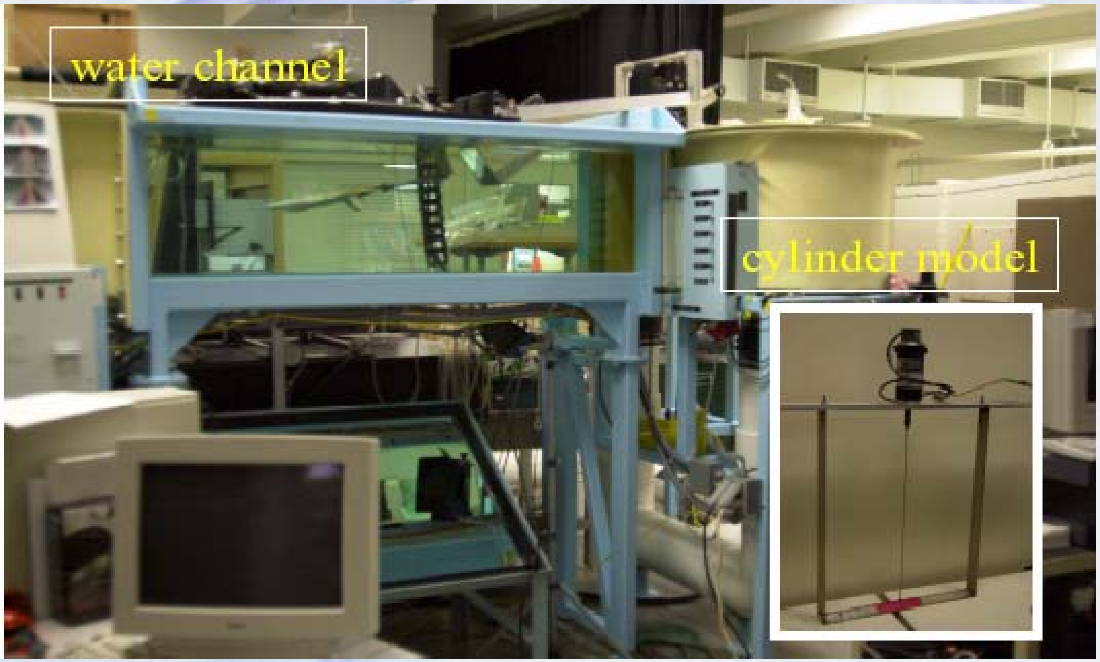
BENCHMARK FOR CLOSED-LOOP FLOW CONTROL

Aeronautics Research Center – March 2002

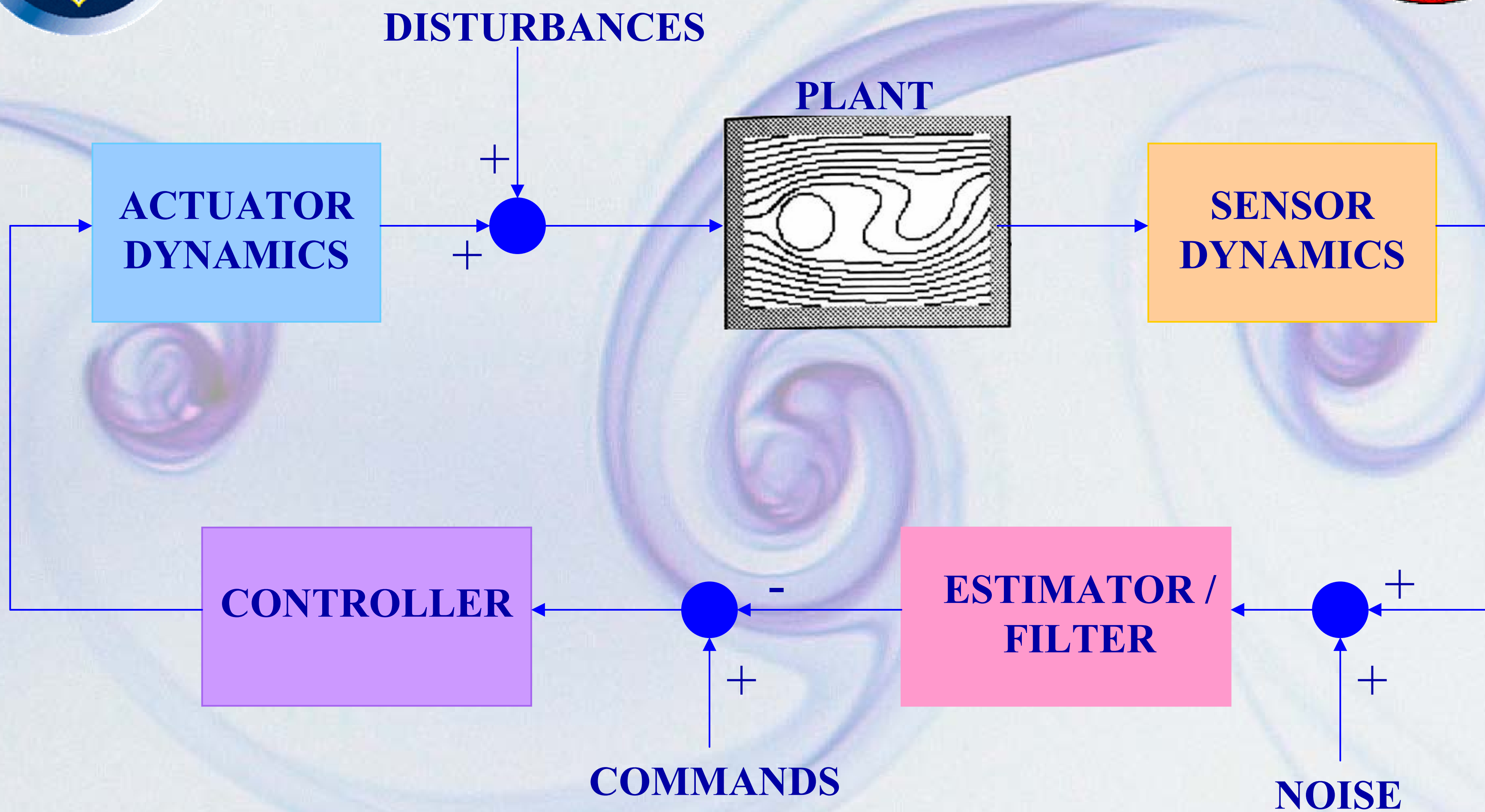
OBJECTIVE

- Better understand the physical mechanisms involved in the closed-loop control of fluid instability, with the ultimate goal of enhancing air vehicle performance.
- Develop a closed-loop robust strategy to suppress the Von-Karman vortex street of a bluff body, thereby decreasing drag and flow-induced vibration.



Circular Cylinder in water tunnel at USAFA

TYPICAL CONTROL SYSTEM ARCHITECTURE ?



PROBLEM

- The state-of-the-art concerning closed-loop flow control is in its infancy.
- The challenges are substantial because of the following:
  – Lack of significant, low-dimensional, design models
  – Lack of effective non-linear, robust, estimation and control strategies
  – Closed-loop flow control problem has yet to be seriously addressed by the control community

ADDRESSING THE PROBLEM

- How can we make flow control problems more accessible to the control community?
- How do we encourage the control community to engage in closed-loop flow control problems by further developing and modifying their individual expertise?
- How can we test and evaluate different potential approaches in a cost effective manner?

PROPOSED APPROACH

Closed-Loop Flow Control

- Develop a series of benchmarks that will enable the control specialist to engage in the problem without necessarily setting up a multi-disciplinary team.
- Provide a forum for the application of a variety of control design methodologies.
- Develop a single experimental system, based on the existing infrastructure at USAFA, which will serve as an impartial T&E center for evaluating different strategies

CLOSED-LOOP FLOW CONTROL BENCHMARK
LEARNING FROM EXPERIENCE

- ❖ **Control Benchmarks: Background**
- ❖ **Elements of a Typical Benchmark**
- ❖ **Control Benchmarks - Success stories**
- ❖ **Details on implementing a benchmark for closed-loop flow control**

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Control Benchmarks: Background

- Many algorithms and devices have been proposed for control, each with its own advantages, depending on the specific application and desired effect.
- In many cases, there has been a lack for definitive studies demonstrating the pros and cons of the different approaches have been unavailable.
- The ability to make direct comparisons between strategies employing various algorithms and devices is necessary to focus future efforts in the most promising directions and to effectively set performance goals and specifications.
- In recent years, several benchmark studies have helped move the control community another step toward the realization and implementation of innovative control strategies.

Note: Adapted from http://www.nd.edu/~quake/benchmarks

Elements of a Typical Benchmark

I

PLANT EVALUATION MODEL – SET OF O.D.E'S

$$\dot{x} = f_1(x, u)$$

x – State Vector

u – Control

II

MEASUREMENT MAPPING

Sensor Output to State Vector

$$y = f_2(x, u)$$

III

BENCHMARK FEATURES

- Plant Uncertainties
- Actuator / Sensor dynamics
- Disturbances and/or Noise

IV

DESIGN CONSTRAINTS & PRACTICAL LIMITATIONS

- **Number and Placement of Sensors**
- **Control Effort**
- **Controller Complexity**

V

CONTROL STRATEGY EVALUATION CRITERIA

- **Performance Measures**
- **Stability Measures**
- **Robustness Measures**

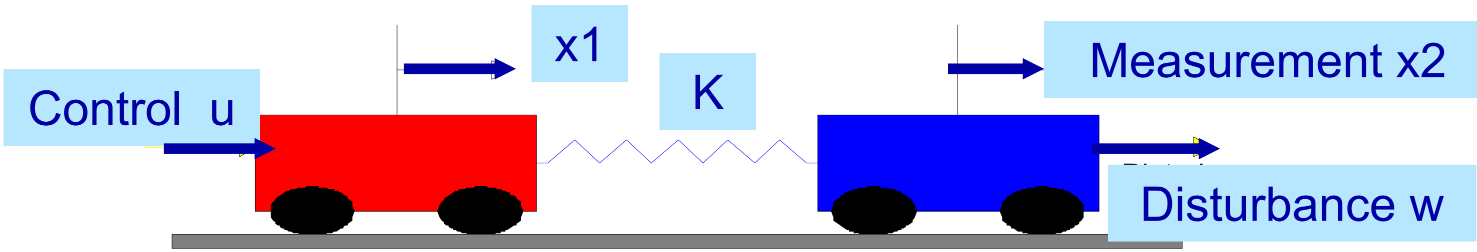
CONTROL BENCHMARKS
Some Success Stories

- ACC (American Control Conference) / AIAA two-mass-spring robust control benchmark.
- NASA Langley Research Center's BACT (Benchmark Active Control Technology) for transonic aeroelastic phenomena.
- ASCE Committee on Structural Control benchmark study in structural control, considering a few benchmark structures, each of them scale models of multi-story buildings.

Success Story I:
Comparing Robust Controllers

- At the 1990-92 American Control Conferences, benchmark problems for robust control design were presented. These benchmarks were developed by Bong Wie of Arizona State University and Dennis Bernstein of the University of Michigan.
- Each of the three problems presented consisted of a two-mass system with an uncertain spring constant and non-collocated sensor and actuator.
- In spite of its simplicity, the problem is non-trivial in that it captures both rigid body mode and flexible body mode with uncertainty.
- By 1992, more than 45 journal and conference papers were published on the above benchmark using a variety of robust control strategies.
- The September-October 1992 issue of the *Journal of Guidance, Control and Dynamics* was dedicated to solutions presented.
- The above issue also contained a paper that utilized a Stochastic Robustness Analysis method to provide a detailed comparison of a collection of designs.

Comparing Robust Controllers



- The spring constant k has a specific nominal value, but is considered uncertain and can vary between known limits.
- A control force u drives the first cart.
- There is an external impulse disturbance w on the second cart that varies with time.
- The only sensor in the system measures the displacement of the second cart alone.
- There is noise in this sensor.

Comparing Robust Controllers

- We want to find u, a minimum-phase controller, that is robust to variations in spring rate, so that we can guarantee a stable system.
- This is a challenging problem because there are large phase lags due to the sensor set-up.
- More conventional methods of design fail due to a lack of robustness.
- Monte Carlo simulations are used within the framework of Stochastic Robustness Analysis (SRA) to examine different control approaches in order to determine winning strategies.

Comparing Robust Controllers

The performance metrics are defined as follows:

- **Probability of Instability** - portrays the likelihood that the variations in the uncertain plant parameter will force at least one closed-loop root into the right half plane.

- **Probability of Settling-Time Exceedance** - portrays the likelihood that the actual response of the targeted state variable will fall outside an arbitrarily chosen envelope.

- **Probability of Control-Limit Exceedance** - portrays the likelihood that the peak actuator displacement will exceed the prescribed saturation limit of unity.

Comparing Robust Controllers

- The Monte Carlo analysis is comprised of three steps, namely:
  - Generation of random spring stiffness;
  - Solution of the deterministic problem for a large number of realizations;
  - Statistical analysis of the results.

- The number of Monte Carlo runs, was selected arbitrarily at 1000 and was found to be adequate.

Comparing Robust Controllers

Controller Description	Design	Nominal Settling Time [s]	Nominal Control Effort	P_I	P_{TS}	P_u
Fixed-order compensators achieving approximate loop-transfer recovery	A	21.0	0.514	0.160	0.971	0.160
Same basic design as A	B	19.5	0.469	0.023	1.000	0.023
Same basic design as A	C	19.7	0.468	0.021	1.000	0.021
H_∞	D	9.9	297.8	0.000	0.000	1.000
Nonlinear constrained optimization	E	18.2	0.884	0.000	1.000	0.000
Structured covariance terms added to linear quadratic Gaussian equations	F	13.7	2.397	0.000	0.633	1.000
Game theoretic controller based on linear exponential Gaussian and H_∞ concepts	G	31.3	1.458	0.000	1.000	1.000
H_∞ using the internal model principle.	H	14.9	0.574	0.000	0.742	0.000
Same basic design as H	I	17.8	0.416	0.000	0.756	0.000
Same basic design as H	J	43.2	1.047	0.039	1.000	0.857
Adaptive fuzzy passive observer based controller	K	8.8	0.53	0.000	0.468	0.042

Success Story II: BACT

- Active control of aeroelastic phenomena, especially in the transonic speed regime, is a key technology for future aircraft design.

- The Benchmark Active Controls Technology (BACT) project is part of NASA Langley Research Center's Benchmark Models Program for studying transonic aeroelastic phenomena.

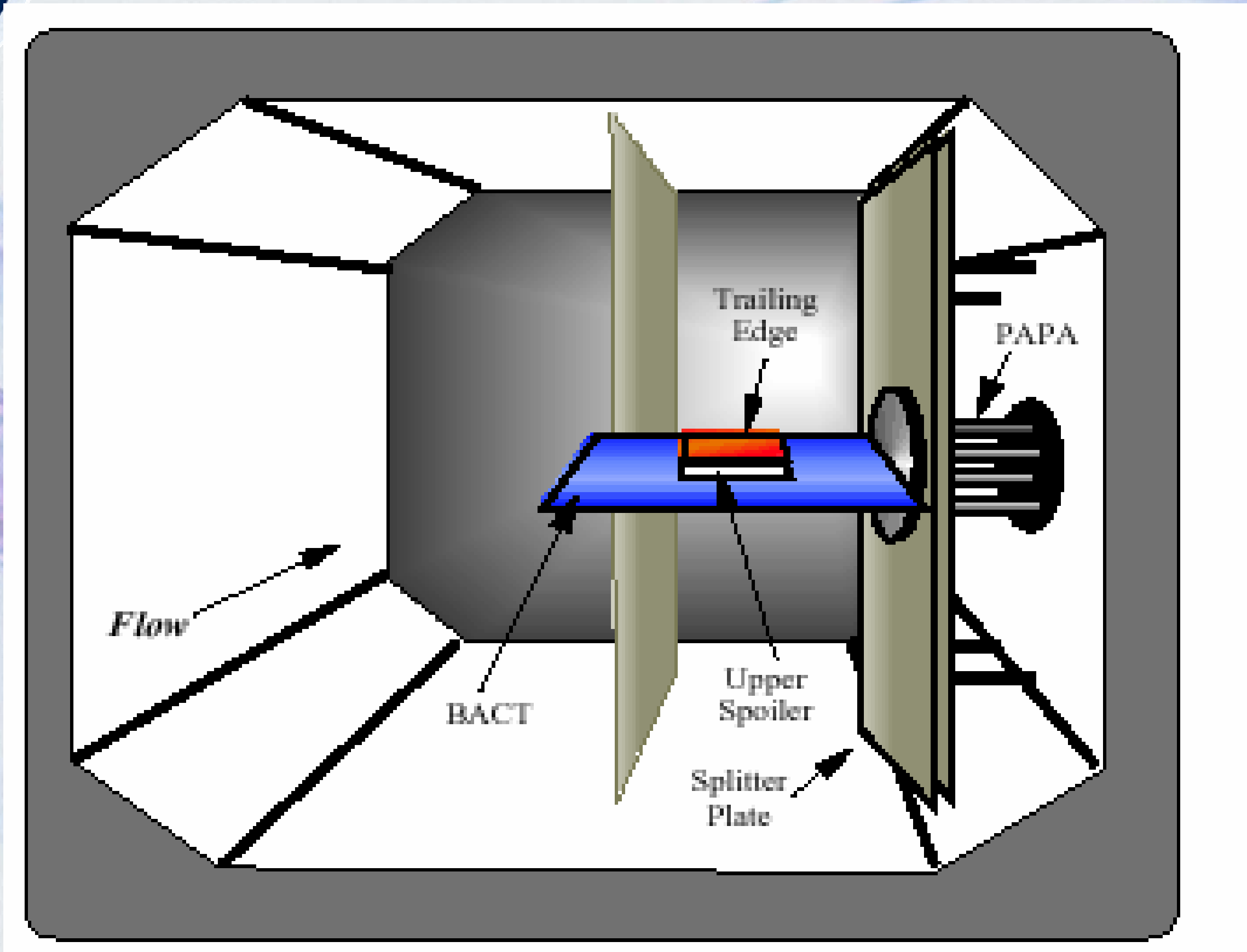
- The BACT wind tunnel model was developed in the late nineties to collect high quality unsteady aerodynamic data (pressures and loads) at transonic flutter conditions and demonstrate flutter suppression by using spoilers (alone and in concert with a traditional trailing edge control surface).

- The availability of truly multivariable control laws also provided an opportunity to evaluate the effectiveness of a controller performance evaluation tool to assess open- and closed-loop stability and controller robustness when applied to multivariable systems.

The BACT Wind Tunnel Model

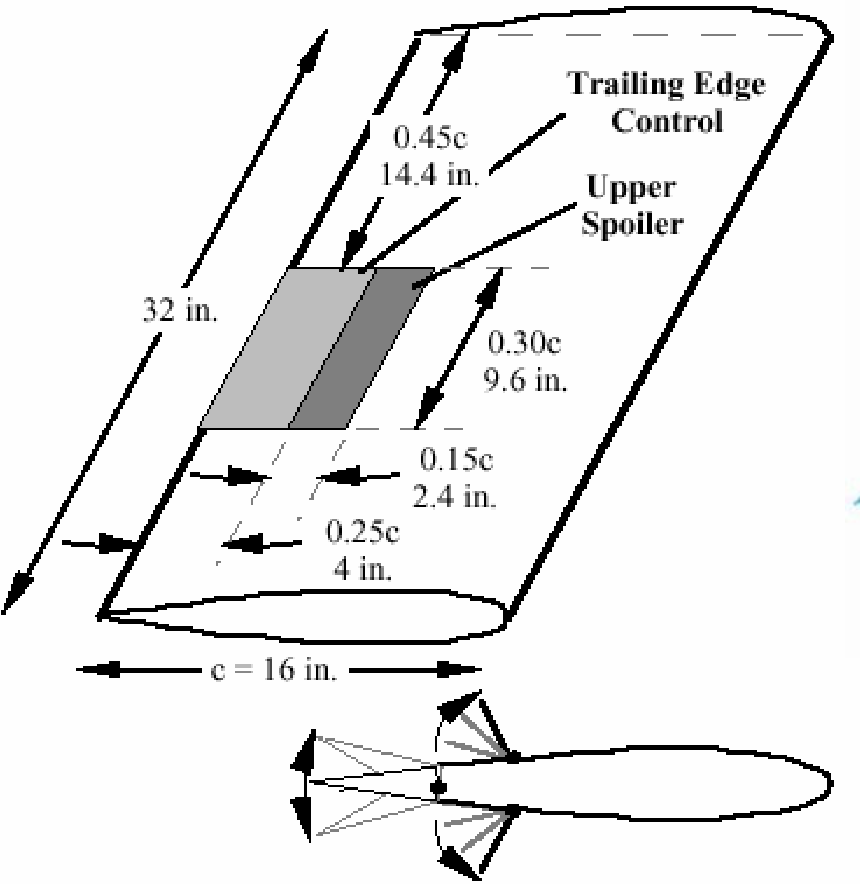
- The BACT is NASA Langley’s wind tunnel model is a rigid rectangular wing with an NACA 0012 airfoil section.
- The wing is equipped with a trailing edge control surface that can be controlled independently.
- A single accelerometer is the primary sensor for feedback control and is located at the wing-shear center.
- In this application, seven working points have been considered with different dynamic pressures.
- The robustness requirement of the desired controller corresponds to acceptable settling times and control effort for each of the working points.

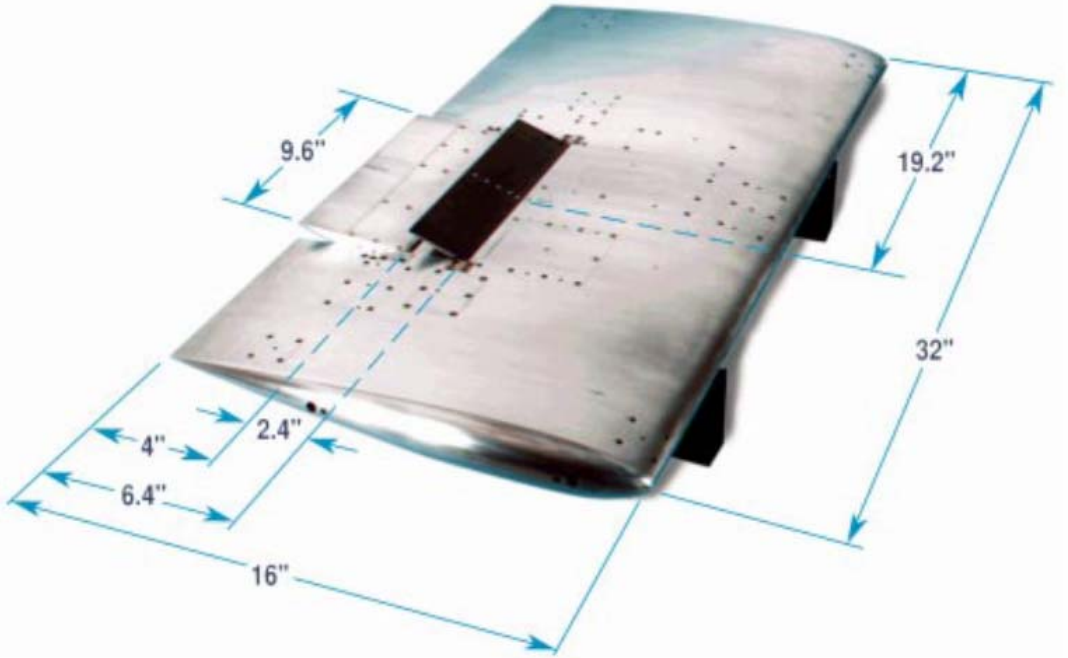
The BACT Wind Tunnel Model



NASA Langley BACT model

The BACT Wind Tunnel Model





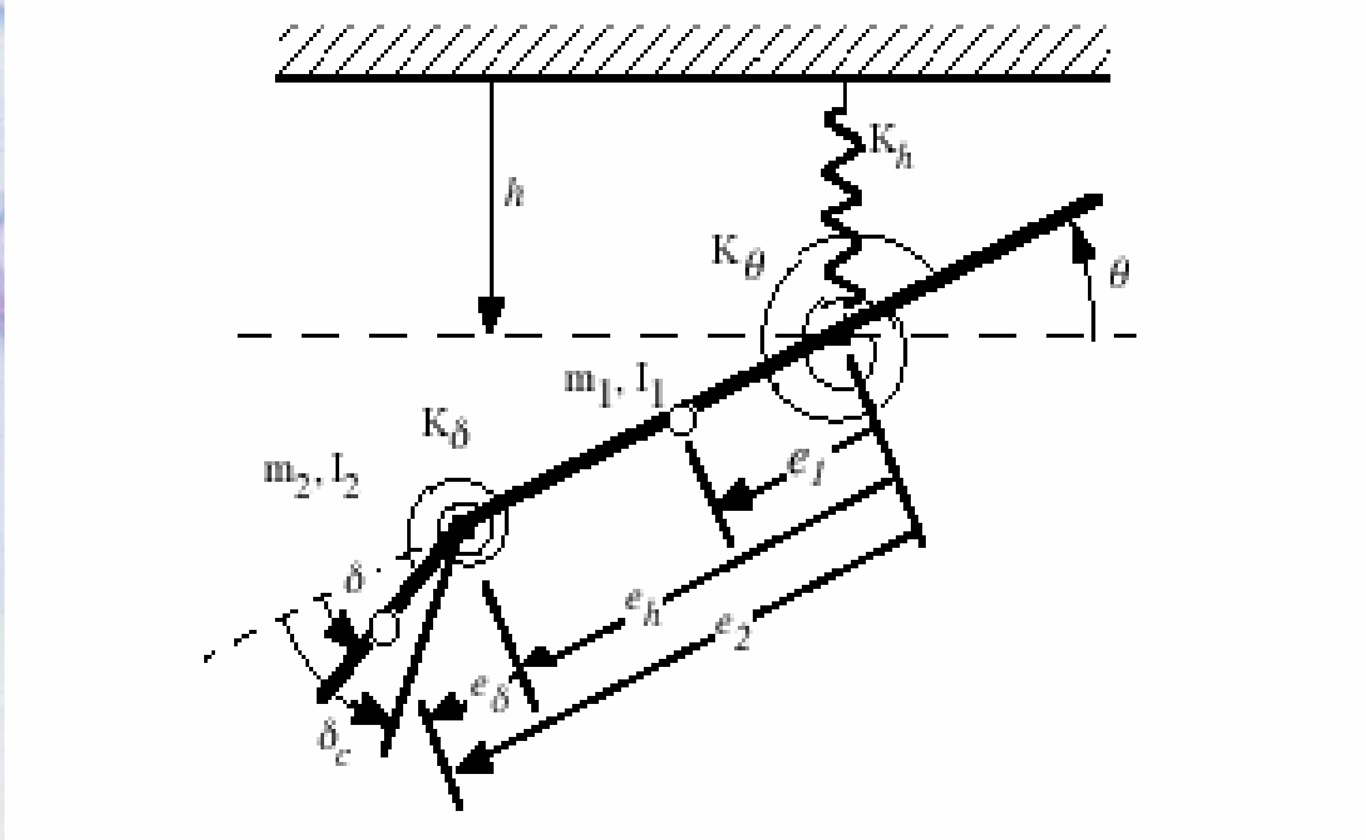
NASA Langley BACT model

BACT-EVALUATION MODEL

- The BACT system has dynamic behavior very similar to the classical two degree of freedom (2-DOF) problem in aeroelasticity.
- This similarity was exploited in the development of the aeroelastic equations of motion for the BACT system by representing it as a 2-DOF system and by using a strip theory aerodynamic approximation.
- The difference between the classical 2-DOF system and the BACT system is primarily the complexity of aerodynamic behavior and presence of additional structural modes.
- The finite span and low aspect ratio of the BACT wing introduce significant three dimensional flow effects.
- The finite span of the control surfaces and their close proximity also introduce significant aerodynamic effects.

BACT: Structural Representation

The BACT system can be idealized as a collection of four rigid bodies corresponding to each of the three control surfaces and the remaining wing element.



BACT:
Optimal Control Problem

For the system

$$\dot{x}(t) = Ax(t) + B\,u(t) + \zeta(t)$$
$$y(t) = Cx(t) + n(t)$$

$$E\left\{\begin{bmatrix}\zeta(t)\\ n(\tau)\end{bmatrix}\begin{bmatrix}\zeta(t) & n(\tau)\end{bmatrix}\right\} = \begin{bmatrix}\Xi & N_f\\ N_f^T & \Theta\end{bmatrix}\delta(t-\tau)$$

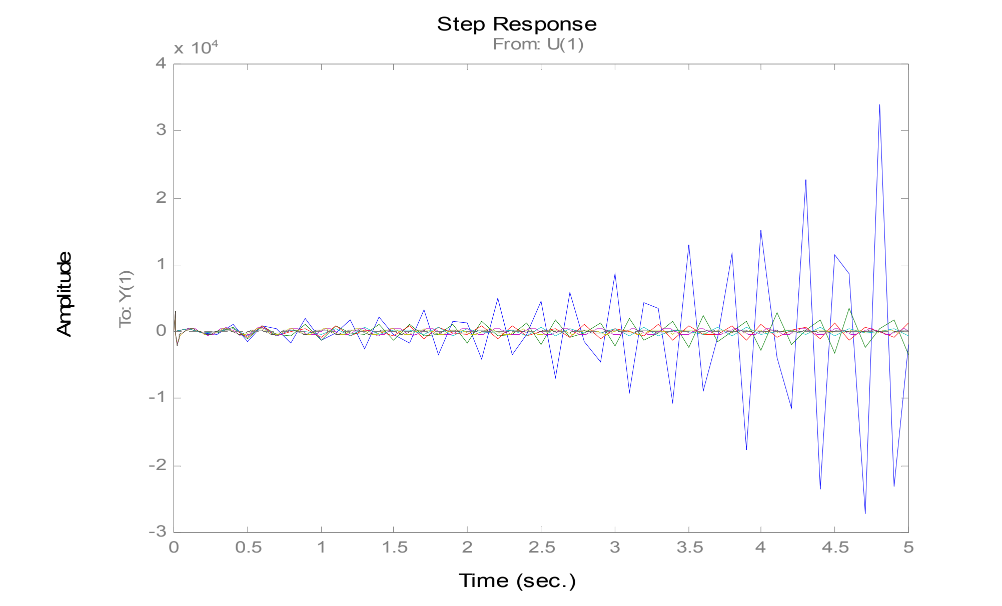
We want to minimize the cost function

$$J = \lim_{T\to\infty} E\left\{\int_0^T [x^T \; u^T]\begin{bmatrix}Q & 0\\ 0 & R\end{bmatrix}\begin{bmatrix}x\\ u\end{bmatrix}dt\right\}$$

Note: The matrix A is q dependent,
i.e. *A=A(q).* B and C are invariant under q.

CONTROL OF BACT PROBLEM

OPEN-LOOP RESPONSE



DESIGN CASE

MEASURE OF COMPARISION	REDUCED ORDER CONTROLLER (LQG)	FUZZY LOGIC CONTROLER
SETTLING TIME (SEC)	7.80	2.62
RMS_{CE} FOR FIRST 5 SEC	1.00120	1.00045
RMS_{CE} FOR FIRST 10 SEC	1.00058	1.00022

- The **OFF-DESIGN** cases represent six, additional working points with different dynamic pressures.
- The settling times of the fuzzy logic controller varies from 1.63 sec. to 2.62 sec.
- On the other hand, the settling times for the reduced LQG controller varies from 2.59 sec. to 7.80 sec.

Success Story III: ASCE Structural Control Benchmark

- The next generation of benchmark structural control studies were initiated by the Working Group on Building Control (chaired by Profs. J.N. Yang, K. Seto and C.S. Yeh) during the Second International Workshop on Structural Control held December 18-20, 1996, in Hong Kong.
- The goal of this effort was to develop benchmark models to provide systematic and standardized means by which competing control strategies, including devices, algorithms, sensors, etc., can be evaluated.
- This goal drove the next generation of structural control benchmark problems, and its achievement took the structural control community another step toward the realization and implementation of innovative control strategies for dynamic hazard mitigation.
- These sessions brought together a group of highly qualified researchers to study two well defined benchmark problems.
- The first benchmark problem focuses on seismically excited buildings. The second proposes a benchmark problem for wind excited buildings.

First Generation Benchmark for Buildings

- The ASCE Committee on Structural Control initiated a benchmark study in structural control, considering two benchmark structures, both scale models of a three-story building, employing an active mass driver (AMD) controller (in the Structural Dynamics and Control / Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame); and an active tendon controller (at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) in Buffalo, New York).
- These structures were chosen because of the widespread interest in controllers and buildings of these types.
- To achieve a high level of realism, evaluation models for these structural system, including the actuator and sensors, were developed directly from experimentally obtained data and form the basis for the benchmark study. In general, controllers that are successfully implemented on the evaluation model can be expected to perform similarly in the laboratory setting (verification of this expectation are in progress in our laboratory). Realistic control constraints and evaluation criteria are included in the benchmark problem definition.
- Problem Definition: Paper and MATLAB data/models (Dec. 1995)
- Simulation Results (Conference): Papers and abstracts from the "Benchmark Structural Control" session at the 1997 ASCE Structures Congress (Portland, Oregon, April 1997)
- Simulation Results (Journal): Papers, abstracts, and simulation results reported in a Special issue of *Earthquake Engineering and Structural Dynamics*, **27**(11) (Nov. 1998)
- Experimental Results: Comparison between simulation and experimental results (in progress)
- Benchmark URL - http://www.nd.edu/~quake/benchmarks/#2GBMP

Second Generation Benchmarks for Buildings

- At the Second International Workshop on Structural Control (Dec. 18-20, 1996, Hong Kong), the Working Group on Building Control developed plans for the "second generation" benchmark studies to include not only competing control algorithms, but entire control strategies, including actuator devices, sensors, etc. Two benchmark problems for the control of buildings have been developed from this initiative and will be presented at the Second World Conference on Structural Control (Kyoto, Japan, June 28 - July 1, 1998).

- **Earthquake-Excited 20-Story Building** This study considers a 20-story steel structure typical of mid- to high-rise buildings designed for the Los Angeles region. The benchmark problem requires a designer to specify actuator type(s) and location(s), controller algorithms, and sensor type(s) and location(s).

  Problem Definition: Paper and MATLAB data/models (Jan. 1998)

- **Wind-Excited 76-Story Building** A 76-story (36 meter) concrete tower, proposed for Melbourne, Australia, subject to wind excitation is the subject of this benchmark problem. A tuned mass damper (TMD) or an active mass driver (AMD) may be installed on the top floor. The designer must choose controller parameters and algorithms.

  Problem Definition: Paper and MATLAB data/models (Yang *et al.*, UC-Irvine, Fall 1997)

- Benchmark URL - http://www.nd.edu/~quake/benchmarks/#2GBMP

Third Generation Benchmarks for Buildings

- At the First World Conference on Structural Control held in Pasadena, the necessity of taking into account the structural non-linearity was identified. During the 2nd World Conference on Structural Control, as a result of the success of the linear benchmark's presented, it was decided to pursue the nonlinear analysis for the seismically excited buildings. Also as a result of the success at the 2nd World Conference on Structural Control, a third generation wind-excited benchmark model was developed. Both benchmark models are listed here.

- **Earthquake-Excited 3-Story, 9-Story and 20-Story Nonlinear Buildings** This study considers three typical steel structures, 3-, 9- and 20-story buildings designed for the SAC project for the Los Angeles, California region. A nonlinear evaluation model has been developed that portrays the salient features of the structural system. The task of each participant in this benchmark study is to define (including sensors and control algorithms), evaluate and report on their proposed control strategies.
  Problem Definition: Paper and MATLAB data/models (2000)

- **Wind-Excited 76-Story Building -** Following the development of the benchmark problem for the response control of a 76-story building in December 1997, wind-tunnel testing has been conducted recently on a 1:400 scale model of the 76-story building to measure wind-load time-history on different floors of the building. The response control performance criterion have been reformulated using experimentally measured wind loads.
  Problem Definition: Paper and MATLAB data/models (Yang *et al.*, UC-Irvine, January 2000)

- Benchmark URL - http://www.nd.edu/~quake/benchmarks/#2GBMP

Benchmarks: Lessons Learnt
Desired Characteristics

- Simple, yet meaningful.
- Generate widespread interest in controllers and systems chosen.
- To achieve a high level of realism, evaluation models for the type of system studied, including the actuator and sensors, should be developed directly from experimentally obtained data and form the basis for the benchmark study.
- In general, controllers that are successfully implemented on the evaluation model should be expected to perform similarly in the laboratory setting.
- Realistic control constraints and evaluation criteria should be included in the benchmark problem definition.

PROPOSED METHOD

- Benchmark I – 1-D, 8 mode POD model of the Ginzburg-Landau equation (non-linear P.D.E. with complex coefficients).
- Benchmark II – 2-D, experimentally verified, POD model of the Navier Stokes equation for cylinder wake.
- Benchmark III – Water-Tunnel experiment of the cylinder wake, capable of translational motion, with real-time PIV for multi-sensor study.

Benchmark I – Salient Features

I

GINZBURG LANDAU EQUATION – POD Model

$$\dot{x} = f_1(x, u)$$

x – State Vector
u – Control

II

MEASUREMENT MAPPING
FEMLAB Output to POD State

$$y = f_2(x, u)$$

III

BENCHMARK FEATURES

- Uncertainty in “Reynolds Number”
- High-Frequency Sensor Noise
- Sensor Output Processing Delay

IV

DESIGN CONSTRAINTS & PRACTICAL LIMITATIONS

- **Maximum Number of Sensors**
- **Control Effort (peak control input)**

V

EVALUATION – STOCHASTIC ROBUSTNESS ANALYSIS

- **Performance Measures**
- **Stability Measures**
- **Robustness Measures**

Benchmark II – Salient Features

I

TRANSLATING CYLINDER

POD Model Based on Experimental/CFD Data

$$\dot{x} = f_1(x, u)$$

x – State Vector

u – Control

II

MEASUREMENT MAPPING

Experimental/CFD Output to POD State

$$y = f_2(x, u)$$

III

BENCHMARK FEATURES

- Uncertainty in “Reynolds Number”
- High-Frequency Sensor Noise
- Sensor Output Processing Delay

IV

DESIGN CONSTRAINTS & PRACTICAL LIMITATIONS

- **Maximum Number of Sensors (placement restrictions)**
- **Control Effort (peak control input)**
- **Controller Complexity (real-time implementation)**

V

EVALUATION – STOCHASTIC ROBUSTNESS ANALYSIS

Based on CFD (COBALT) Truth Model

- **Performance Measures**
- **Stability Measures**
- **Robustness Measures**

Benchmark III – Salient Features

I

TRANSLATING CYLINDER

POD Model Based on Experimental Data

$$\dot{x} = f_1(x, u)$$

x – State Vector

u – Control

II

MEASUREMENT MAPPING

Experimental PIV Output to POD State

$$y = f_2(x, u)$$

III

EXPERIMENTAL BENCHMARK FEATURES

- Re > 100
- Real-time PIV sensing
- PIV Output Processing Delay

IV

DESIGN CONSTRAINTS & PRACTICAL LIMITATIONS

- **Maximum Number of Sensors (placement restrictions)**
- **Control Effort (peak control input)**
- **Controller Complexity (real-time implementation)**

V

EXPERIMENTAL VERIFICATION

Based on Water Tunnel Model at USAFA

- **Performance Measures**
- **Stability Measures**
- **Robustness Measures**

IMPLEMENTATION

1. Development of Benchmark n (n=1,2)
2. Endorsement by AFRL
3. Placement in the Public Domain

4. Call for papers
5. Forum for presentation of approaches

Is Methodology Effective?

If n=1 / Yes → n=n+1

No → Modify strategy

Yes / If n=2 →

6. Modify control strategy to Benchmark III
7. Conduct Experimental T&E at USAFA
8. Compare different control strategies

PAYOFFS

- Increasing the number/quality of control researchers addressing this challenging problem thereby making the process of reaching a “winning strategy” shorter.
- Providing the USAF the possibility of cost-effectively examining a variety of control strategies.
- Focus control community efforts on a *meaningful* fluid dynamic problem.
- Providing the USAF with an objective method of experimentally testing and evaluating competing closed-loop control strategies.

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